THE STRUCTURE AND CONTROL OF THREE-DIMENSIONAL
SHOCK WAVE TURBULENT BOUNDARY LAYER INTERACTIONS

By

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Final Scientific Report
Covering the Period 15 July 1986 thru 30 September 1988

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The present report briefly reviews the work accomplished during the period 15 July 1986 thru 30 September 1988 on the study of three-dimensional shock wave turbulent boundary layer interactions at a Mach number of 3. The work consisted of two major thrusts; 1) modeling of the complex interaction and detailed experiments coordinated with extensive computations; and 2) ~~the~~ exploratory studies of control concepts for a 20° fin and crossing shock configurations. The completed works have been reported and are briefly reviewed. A brief resume is presented of incomplete results on complex interactions, new heat transfer techniques, initial spanwise boundary layer effects, and studies in a new Low Turbulence Variable Geometry Facility. [illegible] flow fields; [illegible]

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ABSTRACT

The present report briefly reviews the work accomplished during the period 15 July 1986 thru 30 September 1988 on the study of three-dimensional shock wave turbulent boundary layer interactions at a Mach number of 3. The work consisted of two major thrusts, modeling of the complex interaction and detailed experiments coordinated with extensive computations, and the exploratory studies of control concepts for a 20° fin and crossing shock configurations. The completed works have been reported and are briefly reviewed. A brief resume is presented of incomplete results on complex interactions, new heat transfer techniques, initial spanwise boundary layer effects, and studies in a new Low Turbulence Variable Geometry Facility.

I. INTRODUCTION

The present report reviews results generated under the subject contract for the period 15 July 1986 thru 30 September 1988.

The overall work statement of the subject contract was to investigate new control concepts for three-dimensional shock wave turbulent boundary layer interactions at Mach 3 by carrying out research on the following four tasks:

1) Use the established flowfield generated by a 20° sharp fin to investigate the effectiveness of several control concepts on the interaction and the flow downstream.

2) Establish the key flowfield features of flows on wedges and cones so that control concepts can be developed for these geometries.

3) Generate surface heat transfer data to better define the interactions and provide another critical test of computational sensitivity to turbulence modeling assumptions (AFWAL support).

4) Interact closely with computational efforts for validation, limits, and when possible, flow structural details, to provide the basis for

extended studies of control concepts.

This proposed program was selected from the many elements of a possible overall program which, in assembly, provided a reasonably optimized way to enhance our understanding of this interaction and its practical applications, linked very closely coordinated computation and experimental programs to get maximum benefit, and explored new concepts of control and downstream effects of these three-dimensional interactions. The program also provided the opportunity (and needs) for the application of new experimental techniques, when available, while applying present techniques to their limit. The program consisted of a core program, with major scheduled events, and a secondary program where important but more limited tests would be included when schedule and staff permitted.

The proposed program was carried out in two concurrent phases. The first phase was the study of the control of three-dimensional interactions and the downstream flows which are generated by them. Initially, control concepts were tried on the well established 20^{o} fin flowfield, with future work planned on wedges and cones. The second phase was primarily concerned with the modelling of three-dimensional shock wave boundary layer interactions generated by fins, and swept wedges to provide a basis for control of these interactions. Both of the above studies were planned to include heat transfer investigations (under AFWAL) and were intimately connected with extensive computational interactions.

Significant progress was made in both phases of the subject program. Completed elements of the work have been written up, presented, and published (Items A-K under Appendix A). The student theses that have been generated by this work are noted in Appendix B. Several pieces of work

are still incomplete, or are currently under investigation. The original planned program was significantly affected by limitations to the compressor plant operation. The test facilities to carry out the proposed studies consisted of the 8" x 8" High Reynolds Number Supersonic Facility and the newly constructed Low Turbulence Variable Geometry Facility. Both of these are driven from a high pressure air supply system. High pressure air storage tanks are pumped to pressures in excess of 3000 psia by a compressor plant consisting of five 100 hp compressors. The compressors, part of the original system in operation since 1946, usually operate with four compressors in continuous operation and a fifth compressor in a stand-by mode. It is used to sustain the pumping capacity while maintenance work is carried out on individual compressors. About six months into the operation of the present contract, and continuing for the following several months, we had a series of major breakdowns which reduced the operating capability to two compressors, approximately cutting in half the available air supply for testing. At the same time, the limited technical staff (which supported both the compressor and the tunnel operation) had to re-orient their efforts to the re-building of the high pressure system. This problem seriously affected the Gas Dynamics Laboratory's capability to carry out the proposed research program. The program was re-oriented to concentrate on key elements which were crucial, while many elements of the program were deferred. Major activities on putting the Low Turbulence Variable Geometry tunnel into operation were deferred, and were only reactivated near the end of the contract. Testing in the 8x8 inch High Reynolds Number Facility was limited, during a major part of the present contract, by the available air

supply rather than by the Laboratory and staff's ability to carry out testing. Supplementary funds provided in the fall of 1987 helped in the re-building of the compressor plant system, and by the end of 1987 three compressors were operational. Work on re-building the fourth compressor was almost completed by the end of the subject contract, but it was not yet operational.

Some special consideration should be noted with regards to the heat transfer technique development carried out under the subject contract. This work, supported by the Wright-Field Flight Dynamics Laboratory (under Dr. Richard Neumann) as part of the present contract, was aimed at trying to develop very high frequency, very high resolution heat transfer measurements. This work was driven by the realization that our previous studies could not provide the most critical tests or comparisons with computation needed to evaluate turbulence models with the conventional instrumentation that was available. The high frequency wall static pressure fluctuations were, of course, not predicted by Reynolds averaged computations and, as noted later in this report, computations to some degree predicted the general shape but not the details of the mean wall static pressure distributions. The obtaining of high frequency, high resolution heat transfer results would provide two key elements. 1) The <u>mean</u> measurements would provide a test of the <u>mean</u> computations, while the high frequency, high resolution results (combined with the wall high frequency static pressure measurements) would provide fundamental information for the modeling and testing of detailed turbulence and wall flow models. The efforts to develop this instrumentation concentrated on very small surface film techniques which, in recent years, due to micro-

circuit technology, seemed to have the potential required. Work on this instrumentation consisted, initially, of the construction and use of a vapor deposition facility. However, once experience had been obtained, the emphasis has been primarily on interacting with industry and other laboratories to try to apply technologies, which they have developed, to our specific problem. This work has resulted, during the final phases of the present contract, with a concept which is being reduced to practicality. The first preliminary results are noted later in this report. Two groups are building elements of the first gauges which will be tested during the coming year.

The following section of the report is a brief review of each of the completed works and some notes on works which were incomplete at the conclusion of the subject contract. A final section details the faculty, staff, and students that were involved in the subject program.

II. WORK COMPLETED DURING THE CONTRACT PERIOD

1) Published papers and presentations

The completed studies have been presented at national and international meetings and are available in printed form as noted in Appendix A. The published results are available as one IUTAM paper, one AGARD paper , two AIAA Journal papers, and seven AIAA preprints, several of which have been submitted for publication in the Journal.

2) Brief review of completed studies

a) The paper by Bogdonoff, entitled "Observation of the Three-Dimensional "Separation" in Shock Wave Turbulent Boundary Layer Interactions," was presented at the 1986 IUTAM Symposium on Boundary Layer

Separation, held at University College, London, in August 1986. The paper details a set of observations obtained during previous studies under OSR support of two- and three-dimensional shock wave turbulent boundary layer interactions. Comparison of the details of specific two and highly swept three-dimensional shock wave turbulent boundary layer interactions resulted in the following observations:

1) three-dimensional flows are radically different than the "classical" two-dimensional flows,

2) the scale, pressure gradients, unsteadiness, and computability are quite different,

3) the designation of "separation" in three dimensions is not realistic, and

4) a concept of vorticity rearrangement is proposed to describe the physics of the interactions in three dimensions.

b) The Journal article by Tan, Tran and Bogdonoff, entitled "Wall Pressure Fluctuations in a Three-Dimensional Shock-Wave/Turbulent Boundary Interaction," Reference B of Appendix A, and the AIAA preprint by Tran and Bogdonoff, entitled "A Study of Unsteadiness of Shock Wave/Turbulent Boundary Layer Interactions from Fluctuating Wall Pressure Measurements," Reference C of Appendix A, detailed the studies of the unsteadiness of shock wave turbulent boundary layer interactions by using multiple high frequency wall static pressure measurements. This unique series of measurements provides, for the first time, some direct evidence of the steadiness of these three-dimensional flows, evaluates the effect of shock pressure ratio, and permits a comparison

of the three-dimensional and two-dimensional cases. Some typical results are shown in Figures 1a and 1b. Figure 1a shows the effect of varying shock pressure ratio while Figure 1b shows the effect of varying the shock generator geometry but keeping the shock pressure ratio constant. In both cases, the rms value is non-dimensionalized by the local mean value, which varies continuously through the interaction. The appearance of a decrease in the fluctuations in the downstream region of the interaction should be noted as a decrease in the percentage fluctuation of a local value which has increased from the initial values. The characteristic shapes of the fluctuating pressures are well established. There is a strong peak in the initial part of the interaction (between the mean upstream influence line and the line of convergence), an approximately uniform region until the location of the theoretical shock wave, and then a slow decrease, with the final values approaching those of the upstream boundary layer (when non-dimensionalized by the local mean values). It is important to note that the general fluctuating pressure level is about half of the two-dimensional case for the same strength shock wave, the general shape of the distribution is similar to the two-dimensional case, and that the flows are far from steady. The source of the disturbing function and the mechanism of the interaction has not been defined from the present experiments.

c) Shapey and Bogdonoff in the paper entitled, "Three-Dimensional Shock Wave/Turbulent Boundary Layer Interaction for a 20° Sharp Fin at Mach 3," Reference D of Appendix A, continued the study of three-dimensional shock wave boundary layer interactions. Detailed flowfield surveys, such as Figure 2, provided the information to construct flowfield models and to interact with the computation of Knight et al. (presented the previous year at the AIAA).

The results shown in Figs. 3 and 4 indicate the considerable differences in the computation and the experiments with regards to surface flow conditions, although the computations reasonably predicted the flowfield details. The paper by Knight, et.al. [Reference E of Appendix A, entitled "Supersonic Turbulent Flow Past a 3-D Swept Compression Corner at Mach 3], made the detailed comparison with the swept compression corner work of Ruderich, Mao and Bogdonoff. It showed that the same general structure of the flowfield was found for both the sharp fin and the swept compression corner, that a significant part of the outer flow appeared to be inviscid-rotational, and that the experiments and computations differed significantly close to the floor.

d) The paper by Kimmel and Bogdonoff, entitled "A Comparative Experimental Investigation of Shock/Turbulent Boundary Layer Interactions Produced by Three Shock Generators," Ref. F of Appendix A, extended the studies of variable strength shock waves generated by the sharp fin to explore the premise that the initial part of the interaction was determined by the shock strength and orientation, independent of the shock generator configuration. A swept corner, sharp fin, and a semi-cone model were designed to generate the same strength and orientation shock wave traced on the floor. The results, shown in Figure 5a and 5b, clearly indicate that the initial part of the interaction is similar for all three shock generators. The different generated shock shapes in the outer flow makes significant differences in this part of the flowfield. It is clear that the general flow structure is primarily determined by the shock strength, with only secondary effects close to the body and the shock being different for the different generators.

Detailed computations of these three geometries have not yet been carried out, but they provide a new and unique set of experiments for computational validation. The computation will also supply the details of the flowfield to check whether the flowfield structure is similar to that obtained for fins and wedges.

e) The paper by Knight, Horstman, Shapey and Bogdonoff entitled "Structure of Supersonic Turbulent Flow Past a Sharp Fin," Ref. G of Appendix A, continued the computation-experiment interaction and provided the base for the construction, for the first time, of a validated flowfield model. The detailed experimental flowfield studies by Shapey and Bogdonoff were compared in great detail to computations by Horstman and Knight. These extensive comparisons, at many stations, showed quite good agreement between the computations and the experimental surveys in most of the flowfield. The pressure distributions, noted in Fig. 6, show that the computations give the general characteristics quite well, but do not closely match the experiments throughout the interaction. Of particular importance is the lack of ability to predict the initiation of the interaction. The report also shows that the local turbulent eddy viscosity from the computations with the different turbulence models were different by almost an order of magnitude in some areas of the flow. However, this appeared to have little effect on the ability of both computations to correctly predict the external flowfield. Of great physical importance was the very detailed streamline tracing carried out with the validated computations. This resulted in the construction of a new mean flowfield model shown in Fig. 7. The mean characteristics shown by this model are the two surfaces shown in the figure. Flow above Surface 2 passes over the interaction and flows

downstream while flow beneath Surface 2 is entrained into a vortical supersonic flow which flows outward approximately in the direction of the inviscid shock wave.

f) The report by Knight et al., Ref. H of Appendix A, extends the computational-experimental interactions to the swept wedge configuration of a 24^{o} wedge swept at 40^{o} and compares this study with that previously carried out for the 24^{o} wedge swept at 60^{o}. The very detailed experiments of Ketchum were compared to the extensive computations of Knight and Horstman using the Reynolds averaged Navier-Stokes equations with two different turbulence models. Comparisons of the computations with the experiments at various points within the flowfield showed reasonable agreement, in most cases, and continued to show little effect of different turbulence models although there were big differences in the turbulent eddy viscosity. There was, however, still a significant difference in the predicted and experimental pressure distributions, Fig. 8. The most notable deficiency of the computations is the lack of ability to predict the upstream influence and the level of the plateau in the middle of the pressure distribution. No turbulence model seemed to be better, in all details, than any other. Nevertheless, with the general flowfield details reasonably predicted, the computations were again used to do streamline tracing and to help develop a flowfield structure as was developed for the 20^{o} fin noted previously. This structure, Fig. 9, shows the same general features as found for the fin interaction. There is a single large supersonic vortical structure flowing out approximately parallel to the wedge leading edge. Two surfaces, similar to that found for the fin are also identified. Surface 2 defines the part of the initial flow which flows over

the vortical interaction. The initiation of Surface 1 is approximately along the line of coalescence, as defined from the surface streaks. A general comparison of the 40° swept wedge with the 60° swept wedge studied previously shows no significant changes in the general flow character, but the detailed examination of the origination of Surface 2 provides some new insight into the interaction. Figure 10 compares the height of Surface 2 for both interactions upstream of the start of the interaction. The difference in character is very noticeable and provides, for the first time, another measure of the flowfield structure to compare with the previous proposals defined from experimental surface visualization and pressures. One could perhaps define an "induction region" and some concept of cylindrical flow, but new definitions and further study will be required before this information can be totally integrated with the experiments which have been carried out and those which are currently underway. The computations, within the limitations of their ability to predict the details, provide a basis for continuing to evaluate the effects of viscosity and the turbulence model.

g) The paper by Bogdonoff entitled "A Study of the Structure of Highly Swept Shock Wave Turbulent Boundary Layer Interactions," Ref. I of Appendix A, presented a detailed overview of the current status of information on highly swept fin and wedge interactions. It started with previously proposed models, detailed the current state of experiments and computations, and presented a series of general observations and conclusions. The unsteadiness of the flows generated by these interactions, usually probed by mean flow measurements and computed by Reynolds averaged equations, is clearly noted on the basis of high frequency surface pressure measurements. The lack of success of the

computations to provide some of the pertinent details may be due to the lack of inclusion of this phenomena, which has not been examined in detail for many of the interactions which have been studied elsewhere. The model of the flow at the fin boundary layer juncture (apex) has been modeled as a detached flow, but exploratory studies of the fin with a gap don't seem to indicate any first order effects on the flowfield details. The experiments and the computations to date are, as yet, unable to define the asymptotic or far flowfield behavior of these interactions. The general proposals (of many years ago) of conical and cylindrical flows are only approximations within the present framework that has been investigated. Current experiments and computation give no indication of internal shocks, jets, or separation. The paper clearly delineates the limits of our present computational capability. Although the general flowfield seems to be reasonably predicted, surface conditions are only approximate at best, and surface details are not predicted at all well by the computation. Even the mean pressure distribution is not very accurate, and there appears to be considerably more difficulty with the swept wedge configurations than with the sharp fin, Fig. 11.

Finally, continued work with the computed flowfield structure (by streamline tracing) and detailed comparison with experiments has suggested the more complete model shown in Fig. 12. This is the best flowfield model currently available and it differs in considerable detail from early flowfield models which postulated separation, free shear layers, and vortices. The structure, as currently defined, is almost entirely supersonic. There is no indication of a vortex formation, but rather a large single vortical structure which encompasses only part of the entering boundary layer. The rest of the boundary layer flows over the interaction and continues downstream as the

initial conditions for the downstream flow. The effect of unsteadiness is still undetermined.

h) The investigation by Toby and Bogdonoff "An Exploratory Study of Corner Bleed on a Fin Generated Three-Dimensional Shock Wave Turbulent Boundary Layer Interaction," Ref. J of Appendix A, was completed during the subject contract but was presented at the AIAA Meeting in January 1989. This is the first of the studies specifically concerned with control, and was formulated after several attempts to change the vorticity in the initial boundary layer was determined to be too complex for a first study. The work concentrated on a 20° fin which was lifted off of the surface. The gap between the fin and the plate varied between 2 and 10 mm, within an initial boundary layer of about 16 mm. Two effects are generated. 1) The apex of the fin is moved into the supersonic region of the boundary layer where the flow can be attached, and the flow under the fin becomes a conical flowfield, impinging on the surface downstream of the leading edge of the fin, and 2) The gap between the fin and the plate (under the influence of the high pressure generated by the 20° deflection and approximately freestream pressure on the back face of the fin) provides a suction along the fin-plate interaction region. At the moment there are no computations for this configuration. Primary data obtained was limited to surface studies of visualization and detailed mean static pressure distributions. The gap appeared to make no significant change in the general flowfield structure. The upstream influence of the interaction moves downstream but the flow behind the inviscid shock location is relatively unaffected, FIg. 13. The bleed under the fin seems to have only a local effect, but this would be expected since the vortical flow is supersonic.

These initial tests did not include any high frequency wall pressure measurements, so the unsteadiness of this interaction with a gap is still unknown. A tentative proposal is that the decrease in the size of the vortical structure is caused by the bleeding off of part of the initial vorticity through the gap, which results in a smaller vorticity and a smaller size of the vortical structure passing spanwise.

i) The report by Batcho et al., entitled "Preliminary Study of the Interactions Caused by Crossing Shock Waves in a Turbulent Boundary Layer," Ref. K of Appendix A, reports the initial results of a control study of a complex interaction. The present study is concerned with a fin generated interaction, interacting with its mirror image, Fig. 14. This phase of the initial study was completed under the subject contract, but presented later, and is the subject of continuing study under current OSR support. Very detailed high resolution mean static pressure measurements were made on the wall for 7-11^{o} symmetric shock crossings. An example of the results are shown in Fig. 15. A comparison of the detailed static pressures on the centerline for varying fin angles is shown in Fig. 16. Surface flow visualization for all conditions was also obtained. Some initial high frequency wall static pressure measurements on the centerline were obtained to give an indication of the steadiness of this flow, Fig. 17. The results presented in Fig. 16 show a rather smooth variation of the mean static pressures, but a peak which exceeds the theoretical inviscid shock crossing value. The high frequency wall static pressure measurements, Fig. 17, show a big difference between the 7-11^{o} case, but the cause and extent of the unsteady phenomena and its structure will have to await further studies of this type. Detailed energy spectra from the wall

pressure measurements seem to show a shift from low frequency for the initial part of the interactions to a peak at a frequency of about 20 kH for the downstream part of the interactions. This report also presents the first test of a high frequency surface temperature gauge which will be used to measure heat transfer. This gauge, approximately 1 mm x 1 mm, seems to have a frequency response approaching that of the Kulite high frequency pressure gauges. Preliminary results of a single test of the gauge located behind the crossing point of the 11^{o} interaction seems to indicate very large heat transfer fluctuations (greater than 100%) where the pressure fluctuations are also very high.

III. STUDIES INITIATED BUT NOT COMPLETED

a) As noted in Section II.i, only the first part of the study of crossing shock wave interactions has been completed under the subject contract. The model, which was constructed to carry out these tests, provides a unique capability, only part of which was used under the subject contract. The model-test section is shown in Fig. 18a-c. In Fig. 18a, the test section with the model installed is shown removed from the 8" x 8" High Reynolds Number Tunnel. When installed, the front face of the test section would be attached to the nozzle section of the tunnel generating the Mach 3 flow. For size reference, the width and height of the opening is 8" to match the exit of the supersonic nozzle. In Fig. 18a the leading edges of the two test plates are clearly seen, each located 2" off the respective top and bottom walls. In Fig. 18b, the top section of the test section has been removed, the leading edge of both plates can be clearly seen, and the upper surface of the top plate is visible. A large rectangular section has been removed and one can see the downstream part

of the two shock generators. The shock generators are driven to various angles by the two threaded drives noted on each side of the test section. In Fig. 18c, the top plate has been completely removed to make the full shock generators (fins) clearly visible. The rectangular sections noted in the plate are replaceable instrumentation sections which can carry a wide variety of sensors. By moving the sections, the instrumentation can be located as desired. For example, the static pressure plates located in different position provide approximately 3000 static pressure points located on about 0.10" centers over the entire plate area of interest. The instrumentation plates also carry high frequency static pressure gauges and high frequency heat transfer gauges now under development. Provisions have been made to survey the entire flowfield by probes through the top wall and optical access to the interaction can be obtained by placing a glass sheet in the top plate (replacing the rectangular opening noted in Fig. 18b) and using a glass plate in the circular frame at the top of the test section noted in Fig. 18a.

This complex model has been designed to be extremely flexible, covering a range of long term needs for the study of complex interactions. The geometry, as used in its initial form, provided an entering boundary layer by using sharp flat plates as the top and bottom walls of the interaction. The leading edges of the flat plate are approximately 6" ahead of the shock generators. The initial tests were carried out with symmetrical fin configurations, that is both shock generators were at the same angle. For computation, this provided two planes of symmetry and permitted the option of detailed computations to be carried out in only one of the four quadrants. Although the desired fin angle range was from 3 or 4 degrees to choking of the configuration, in the initial tests the minimum angles were limited to 7^{o}. For the symmetrical

configuration, 11^{o} was the maximum angle before choking occurred.

The model provides considerable capability for extensions of these early tests. Nonsymmetrical fin configurations can clearly be carried out, providing only one plane of symmetry. The flat plates can be extended or cut back to provide different thicknesses of the boundary layer entering the interaction. The bottom plate could be removed and the fins extended to the bottom floor. This would provide an interaction with a thick boundary layer on the bottom and a thin boundary layer on the top, a condition which simulates the <u>real</u> problems of inlets on vehicles. In addition, a flat plate can replace one of the shock generators, providing a framework for the study of shock reflection. Current contracts with OSR will exploit much of this capability.

b) The development of high frequency, very small heat transfer gauges, has been a long and difficult one, but a final solution is within sight. Current interactions with NASA-Langley and Calspan have developed the details and techniques for the final gauges. During this development, NASA-Langley provided a gauge developed for other requirements, Fig. 19. It is this gauge which provided the preliminary results noted in Section II.i. Both NASA-Langley and Calspan are currently building elements of the final gauges. The sensitive elements will be linear elements approximately 1 mm long but only a few microns in width, comparable to one leg of the serpentine pattern of Fig. 19. If successful, the elements being developed will be assembled into gauges which will provide a hundred elements per squre inch, and which can be built in arrays large enough to cover a significant fraction of the interaction region. This activity is being continued under current OSR support.

c) One experimental study was completed but the analysis of the results are still incomplete. Wang, Mao, and Bogdonoff examined a problem fundamental to

all three-dimensional interactions, the effect of varying boundary layer characteristics in the lateral direction. For highly swept interactions, the boundary layer far from the apex is usually considerably thicker than that at the apex. Although the general concept is that the flowfield scales with boundary layer thickness, there has not been a definitive test which supports or refutes this hypothesis. The use of the average boundary layer thickness along the interaction, the boundary layer thickness at the apex, or the local boundary layer thickness at each point along the interaction has not been clearly defined. Wang, et al. set out to study this effect by using a swept plate geometry to get approximately constant boundary layer thickness along the interaction for a swept compression corner, Location A of Figure 20. A similar but mirror image geometry was located at Location B for a second test. The boundary layer thickness at the apex of both models was the same, but clearly the distribution of boundary layer thickness along the interaction was quite different for the model at location A and at location B. A full series of pressure distributions and surface flow visualization data were obtained, but the analysis has not been completed because of Mrs. Mao's departure.

d) For several years the Gas Dynamics Laboratory has been building a new facility, the Low Turbulence Variable Geometry Facility shown in Fig. 21. This facility was designed with two unique features: 1) the very low turbulence settling chamber and 2) the capability to arrange the diffuser so that the flow leaving the test section did not unnecessarily have to stay along the axis of the nozzle. The proposed shake-down and calibration of this tunnel and its use to explore, in the first instance, any differences in test results for two- and three-dimensional shock wave turbulent boundary layer interactions in different facilities, was not completed because of the compressor plant

breakdown. The tunnel itself was completed and fully assembled. It was then disassembled, the screens removed, and a dummy nozzle with the correct throat and test section size installed for the initial shake-down tests. A test section from the 8" x 8" High Reynolds Number Tunnel (in the straight line configuration) was installed and, under current OSR support, the shake-down tests and calibration are being carried out.

IV. FACULTY, STAFF AND STUDENTS INVOLVED IN THE PROGRAM

Professor Bogdonoff was the primary faculty involved in the program with some inputs from Professor Smits. The students involved in the program were:

P. Batcho, Ph.D. - August 1987 thru present
A. Ketchum, MSE - September 1986 thru November 1988
R. Kimmel, Ph.D. - July 1982 thru October 1986
W. Konrad, MSE - September 1988 thru present
K. McGinley, MSE - September 1988 thru present
B. Shapey, MSE - September 1985 thru October 1986
S. Toby, MSE - September 1986 thru September 1988
T. Tran, Ph.D. - July 1981 thru August 1986
D. Trevas, MSE - July 1986 thru June 1987 (did not complete MSE program)

Dr. Ruderich was deeply involved in the program until he left in September of 1986, at which time Dr. Watmuff joined the program (25% time) working with Prof. Bogdonoff. He left in November 1987. Mrs. M.-F. Mao, a visiting research engineer from Beijing, China, was involved with the research thru January 1987. Dr. Emerick Fernando was involved with the research in September 1988.

APPENDIX A:

Published Papers & Presentations

A) Bogdonoff, S. M., "Observation of the Three-Dimensional "Separation" in Shock Wave Turbulent Boundary Layer Interactions," Presented at the 1986 IUTAM Symposium on Boundary-Layer Separation, University College, London, August 1986.

B) Tan, D.K.M., Tran, T. T. and Bogdonoff, S. M., "Wall Pressure Fluctuations in a Three-Dimensional Shock-Wave/Turbulent Boundary Interaction," AIAA Journal, Vol. 25, No. 1, January 1987, Pg.14.

C) Tran, T. T. and Bogdonoff, S. M., " Study of Unsteadiness of Shock Wave/Turbulent Boundary Layer Interactions From Fluctuating Wall Pressure Measurements," AIAA 25th Aerospace Sciences Meeting, Paper #87-0552, Reno, Nevada, January 12-15, 1987.

D) Shapey, B. and Bogdonoff, S. M., "Three-Dimensional Shock Wave/Turbulent Boundary Layer Interaction for a 20^{o} Sharp Fin at Mach 3," AIAA 25th Aerospace Sciences Meeting, Paper #87-0554, Reno, Nevada, January 12-15, 1987.

E) Knight, D., Horstman, C. C., Ruderich, R., Mao, M.-F. and Bogdonoff, S., "Supersonic Turbulent Flow Past a 3-D Swept Compression Corner at Mach 3," AIAA 25th Aerospace Sciences Meeting, Paper #87-0551, Reno, Nevada, January 12-15, 1987.

F) Kimmel, R. L. and Bogdonoff, S. M., "A Comparative Experimental Investigation of Shock/Turbulent Boundary Layer Interactions Produced by Three Shock Generators," AIAA 19th Fluid Dynamics, Plasma Dynamics and Lasers Conference, Paper #87-1366, Honolulu, Hawaii, June 7-10, 1987.

G) Knight, D. Horstman, C., Shapey, B. and Bogdonoff, S. M., "Structure of Supersonic Turbulent Flow Past a Sharp Fin," AIAA Journal, Vol. 25, No. 10, October 1987.

H) Knight, D., Raufer, D., Horstman, C., Ketchum, A. and Bogdonoff, S. M., "Supersonic Turbulent Flow Past a 3-D Swept Compression Corner at Mach 3 - Part II," AIAA Paper #88-0310, AIAA 26th Aerospace Sciences Meeting, Reno, Nevada, January 1988.

I) Bogdonoff, S. M., "A Study of the Structure of Highly Swept Shock Wave Turbulent Boundary Layer Interactions," Presented at the AGARD Fluid Dynamics Panel Symposium on 'Fluid Dynamics of Three-Dimensional Turbulent Shear Flows and Transition,' Cesme, Turkey, October 1988.

J) Toby, A. Steven and Bogdonoff, S. M., "An Exploratory Study of Corner Bleed on a Fin Generated Three-Dimensional Shock Wave Turbulent Boundary Layer Interaction," AIAA Paper #89-0356, AIAA 27th Aerospace Sciences Meeting, Reno, Nevada, January 1989.

K) Batcho, P. F., Ketchum, A. C., Bogdonoff, S. M. and Fernando, E. M., "Preliminary Study of the Interactions Caused by Crossing Shock Waves and a Turbulent Boundary Layer," AIAA Paper #89-0359, AIAA 27th Aerospace Sciences Meeting, Reno, Nevada, January 1989.

APPENDIX B:

THESES

A) Shapey, B. L., "3-D Shock Wave/Turbulent Boundary Layer Interaction for a 20° Sharp Fin at Mach 3," MSE, October 1986.

B) Tran, T. T., "An Experimental Investigation of Unsteadiness in Swept Shock Wave/Turbulent Boundary Layer Interactions," Ph.D., April 1987.

C) Kimmel, R. L., "An Experimental Investigation of Quasi-Conical Shock Wave/Turbulent Boundary Layer Interactions," Ph.D., April 1987.

D) Toby, A. S., "Exploratory Experiments in Vorticity Control in Shock Wave-Boundary Layer Interactions," MSE, September 1988.

E) Ketchum, A. C., "Analysis of the Flowfield Structure of Several Three-Dimensional Shock Wave-Boundary Layer Interactions from Detailed Static Pressure Measurements," MSE, November 1988.

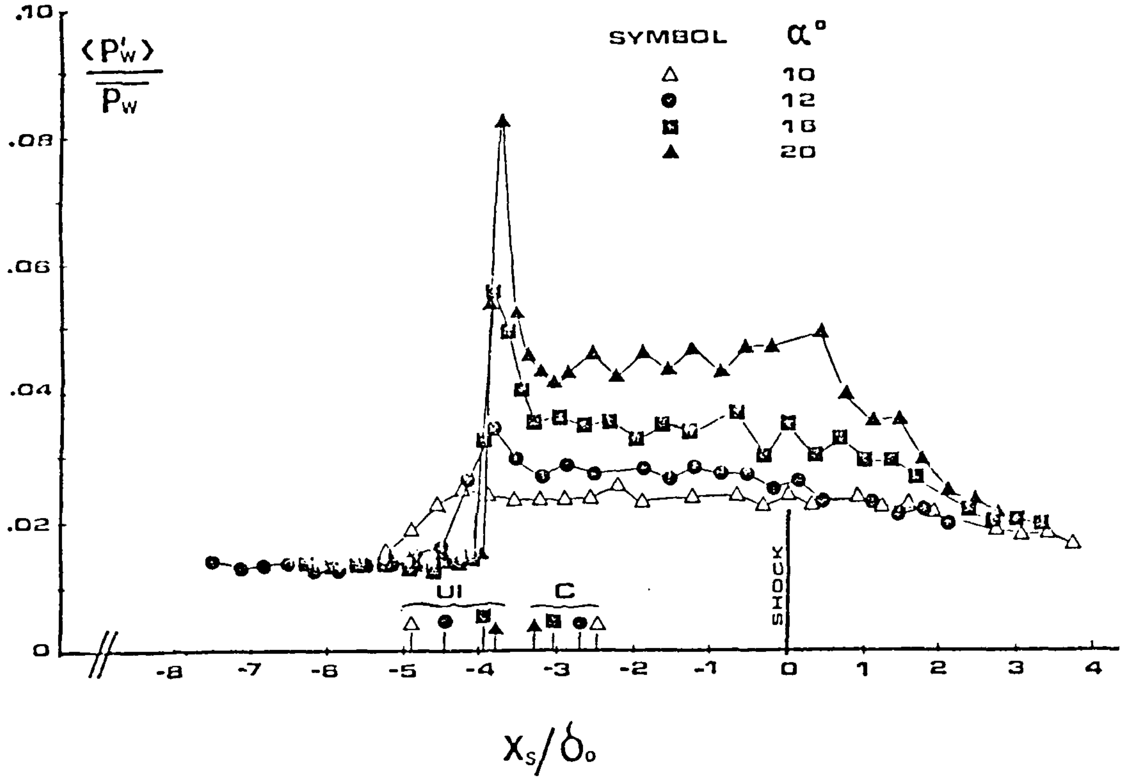


Figure 1a. Distribution of rms of wall pressure fluctuation for fin interactions. Normalized by local mean pressure.

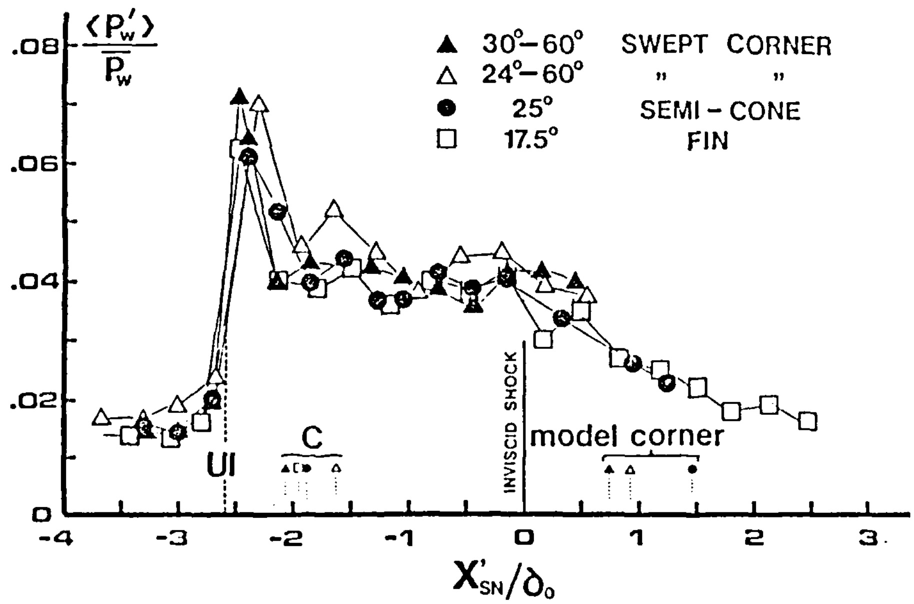
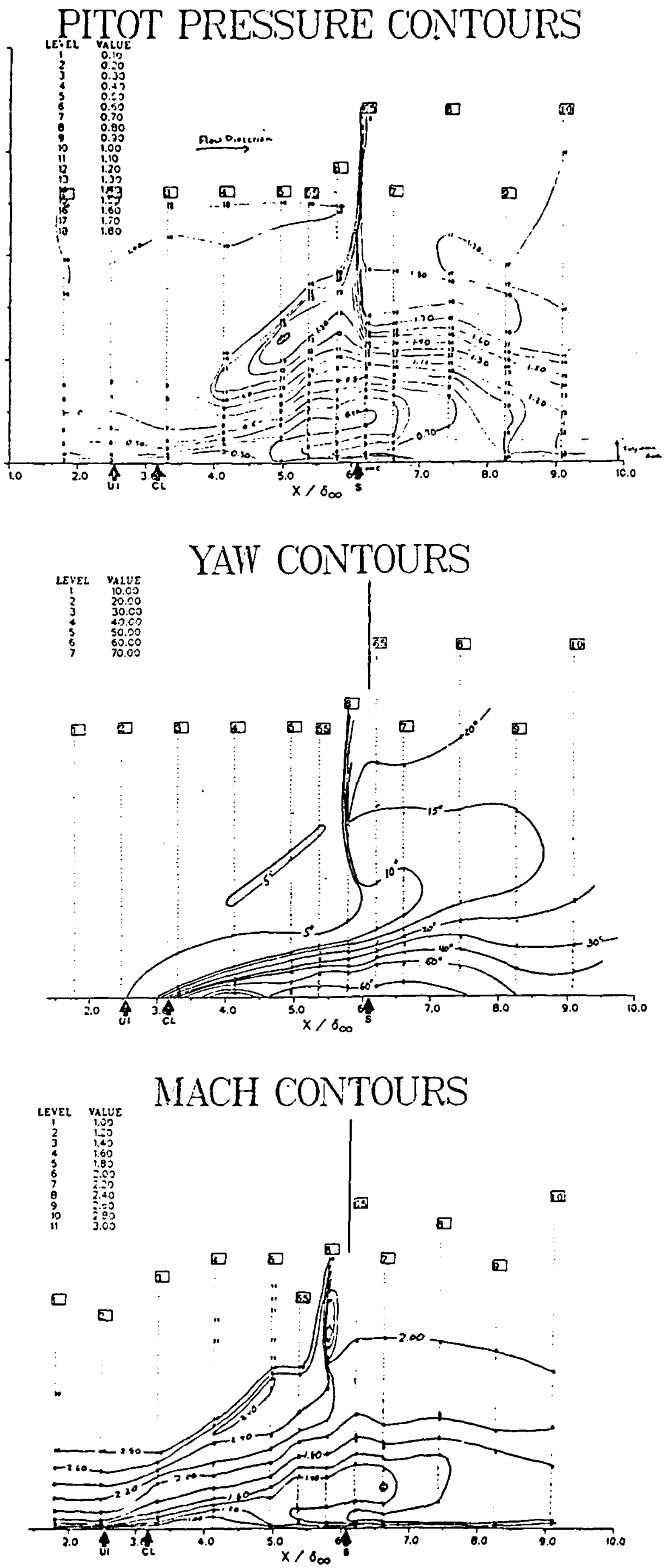


Figure 1b. Distribution of rms of wall pressure fluctuation for different shock generators. Normalized by local mean pressure. (Data from Kimmel and Ruderich and Mao.)



a) pitot pressure

b) yaw angles

c) Mach number

Figure 2. Flowfield data for the 20° fin.

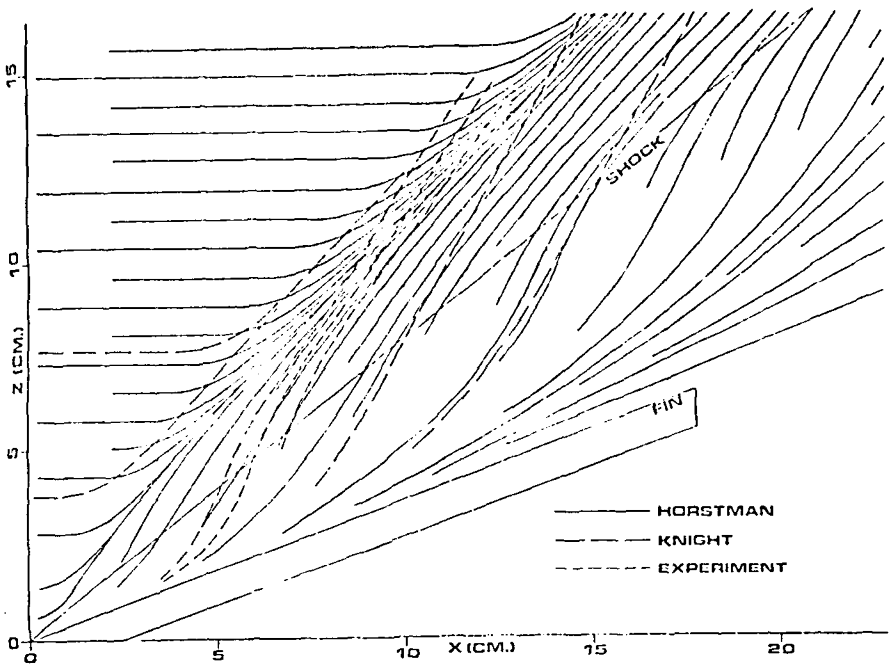


Figure 3. Computed and measured surface streaklines.

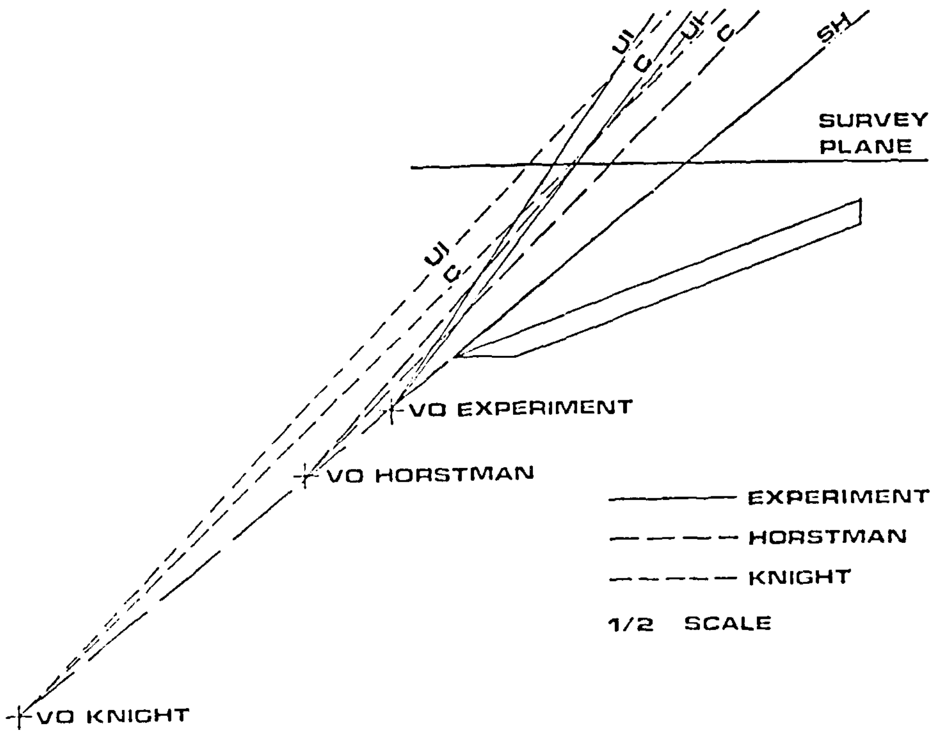


Figure 4. Experimental/computed upstream influence, coalescence, virtual origin.

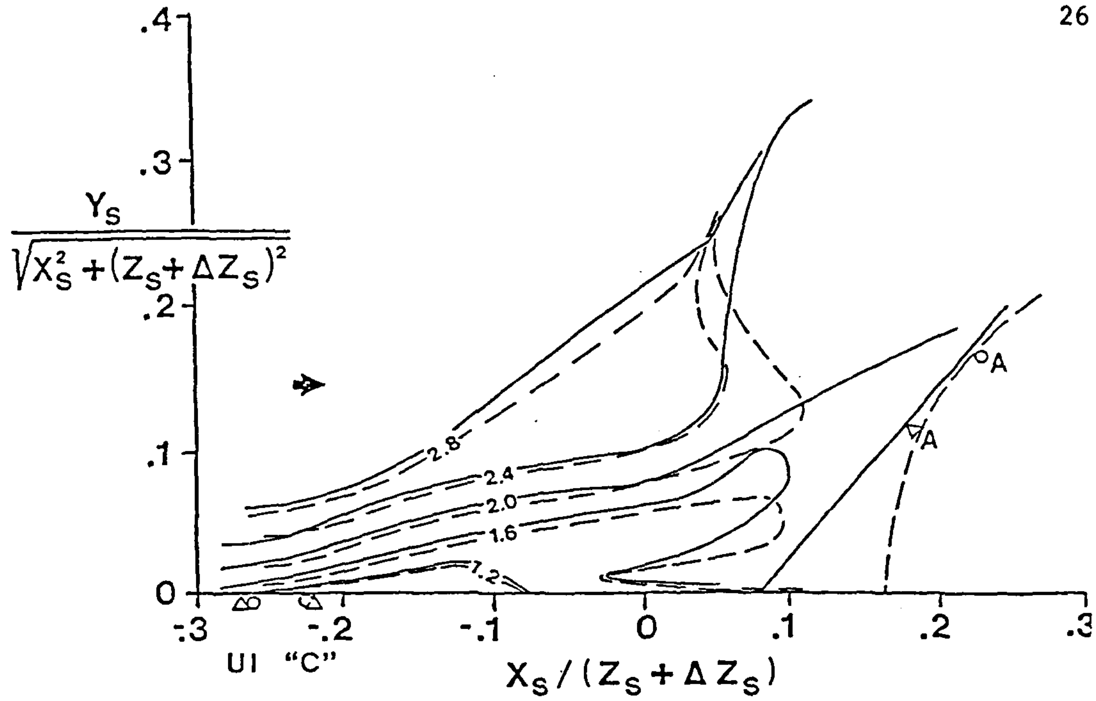


Figure 5a: $\alpha=30°$, $\lambda=60°$ Swept corner [solid] and $\gamma=25°$ semicone [dashed] Mach contours.

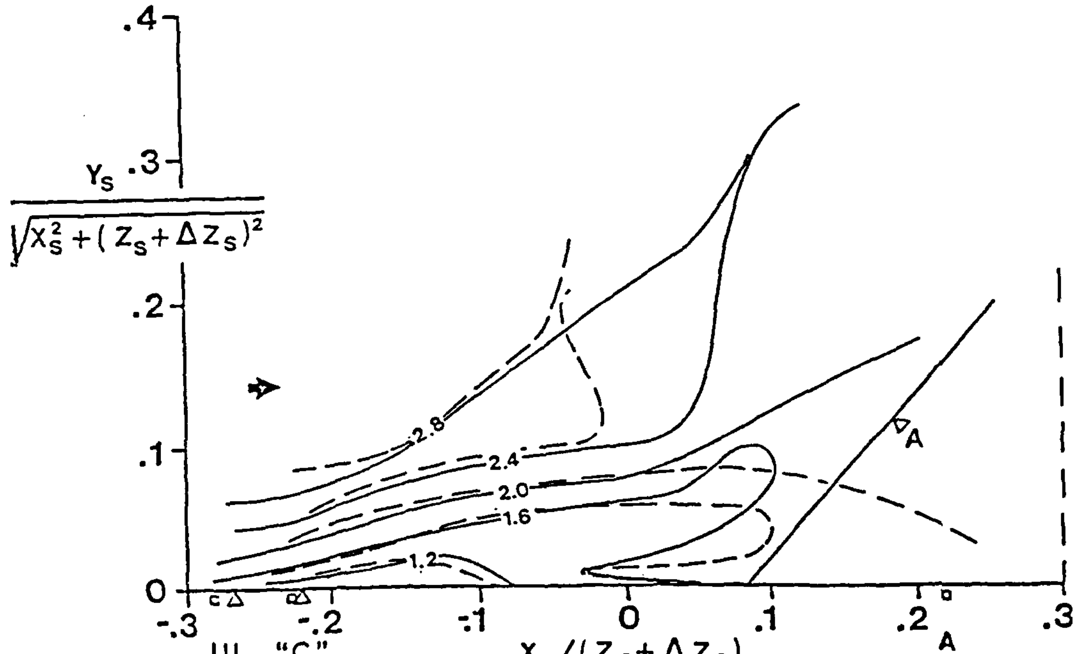


Figure 5b: $\alpha=30°$, $\lambda=60°$ Swept corner (solid) and $\alpha=17.5°$ fin (dashed) Mach contours.

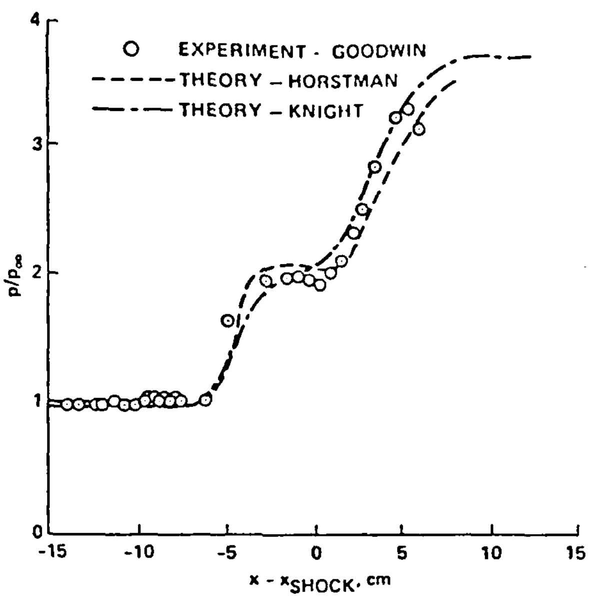


Figure 6. Surface pressure at $z = 6.8\delta_x$

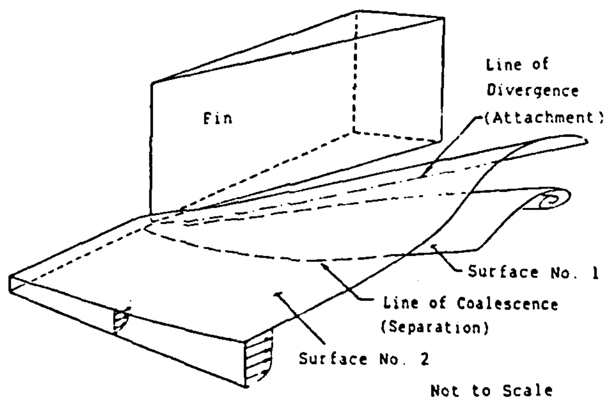


Figure 7. Mean flowfield structure.

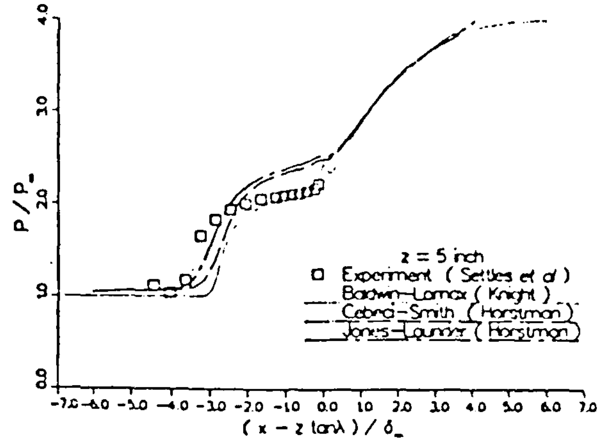


Figure 8. Surface pressure at $z = 10.1\delta_\infty$ for $Re_{\delta_\infty} = 8.1 \times 10^5$.

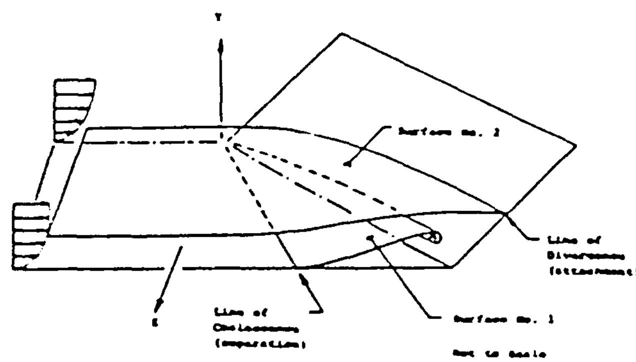


Figure 9. Flowfield structure for 3-D swept compression corner.

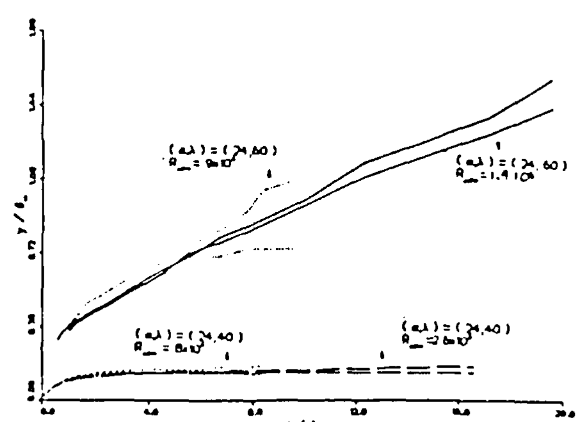
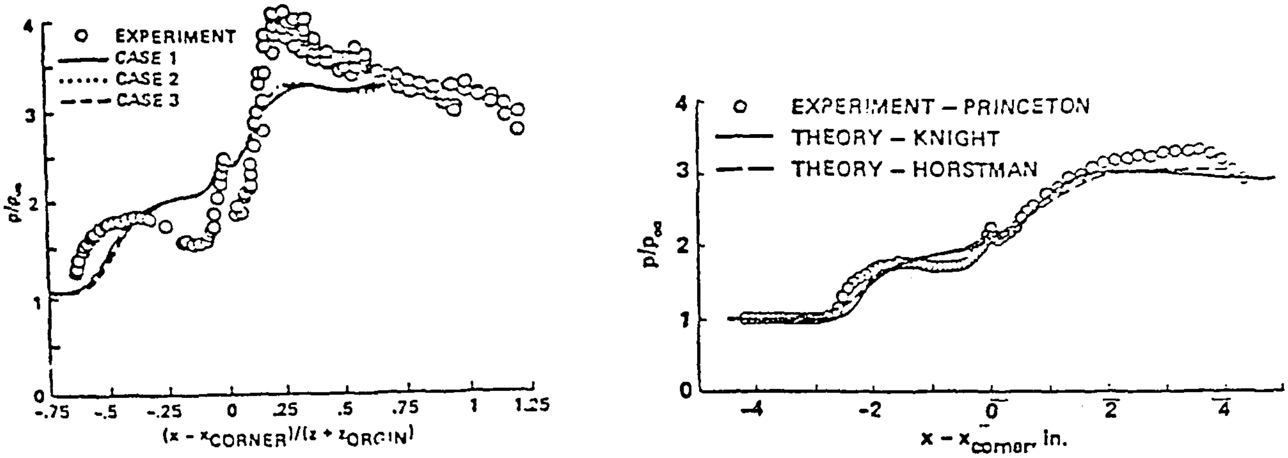


Figure 10. Height of Surface 2 for (α,λ) = (24,40) and (24,60) degrees.



a) b)

Figure 11. Comparison of computation and experiment for a 3-D swept compression corner, α = 24°, λ = 60°.

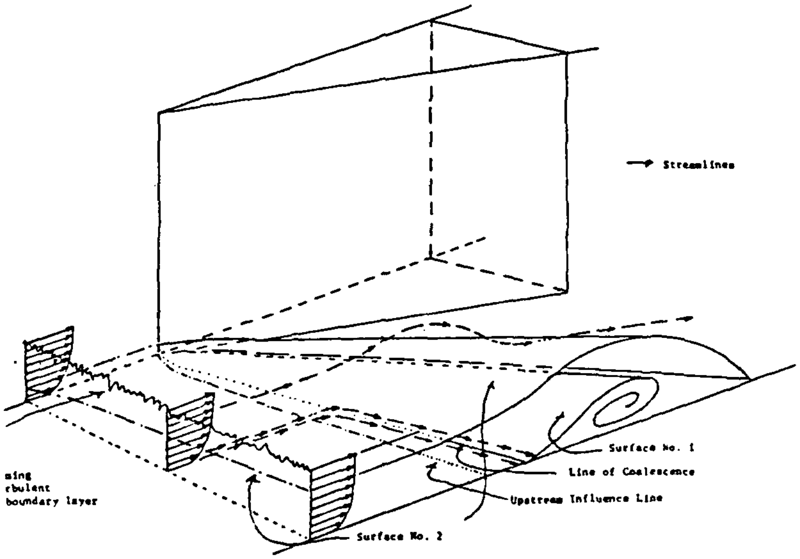


Figure 12. Flowfield structure (not to scale).

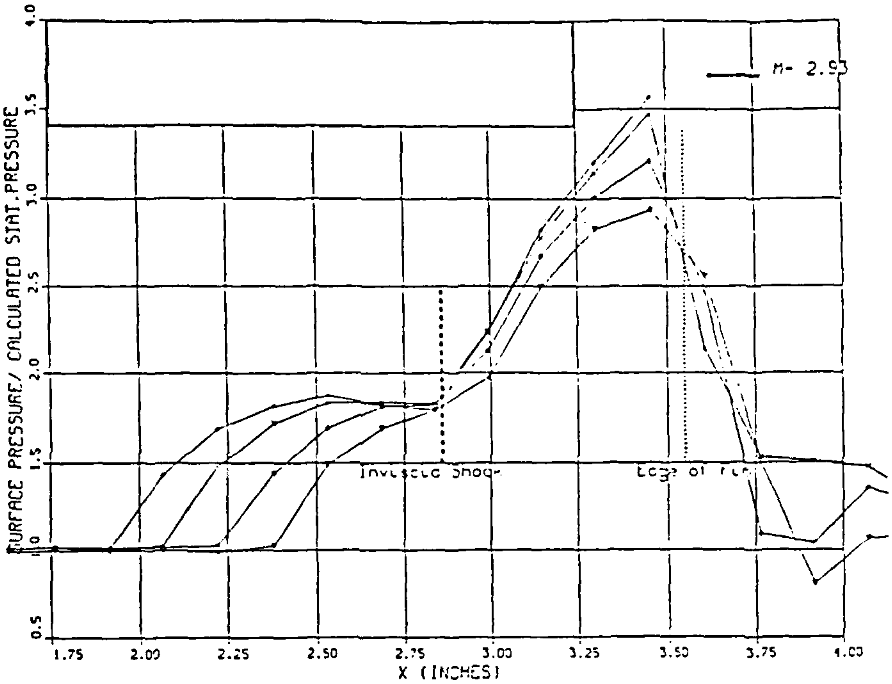


Figure 13. Pressure trace perpendicular to shock.

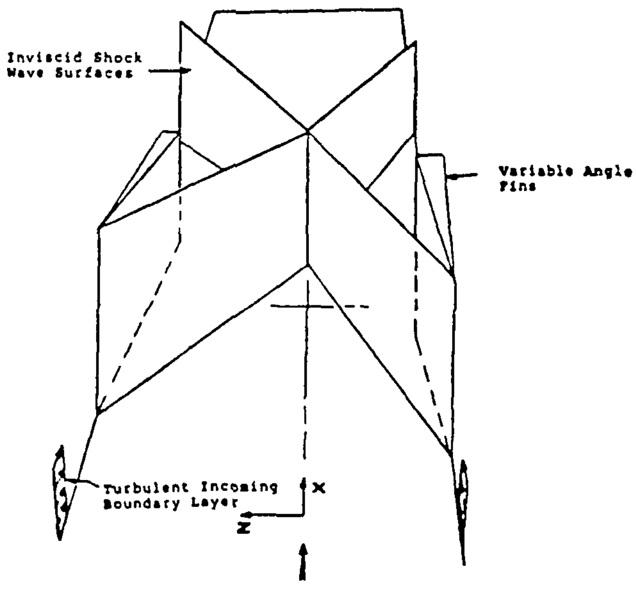
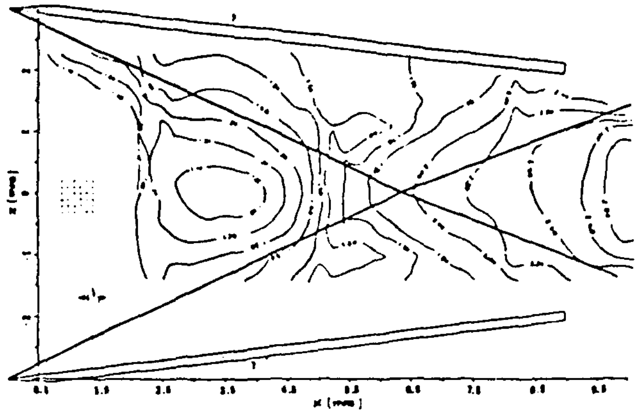
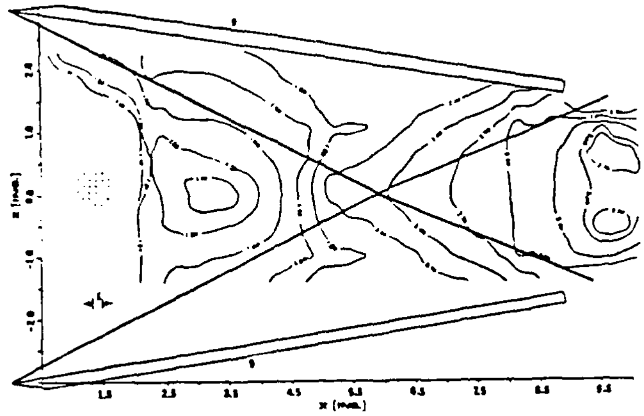


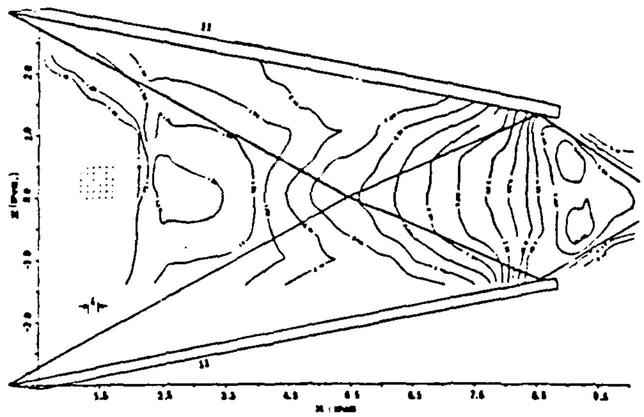
Figure 14. Crossing shock boundary layer interaction.



a) 7° Symmetric Interaction.



b) 9° Symmetric Interaction.



c) 11° Symmetric Interaction.

Figure 15. Constant surface static pressure contours for symmetric interactions.

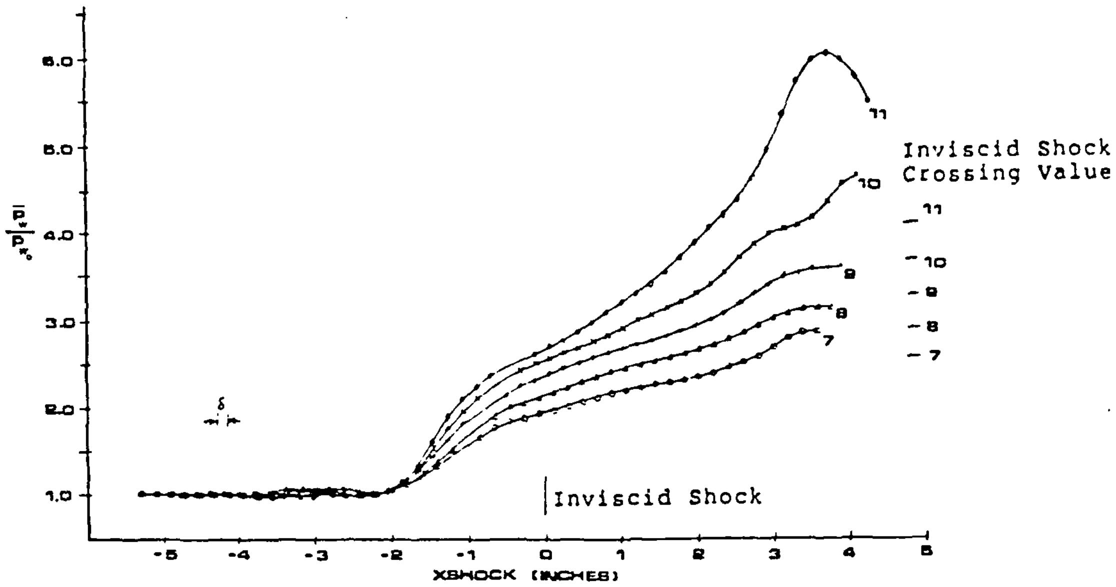
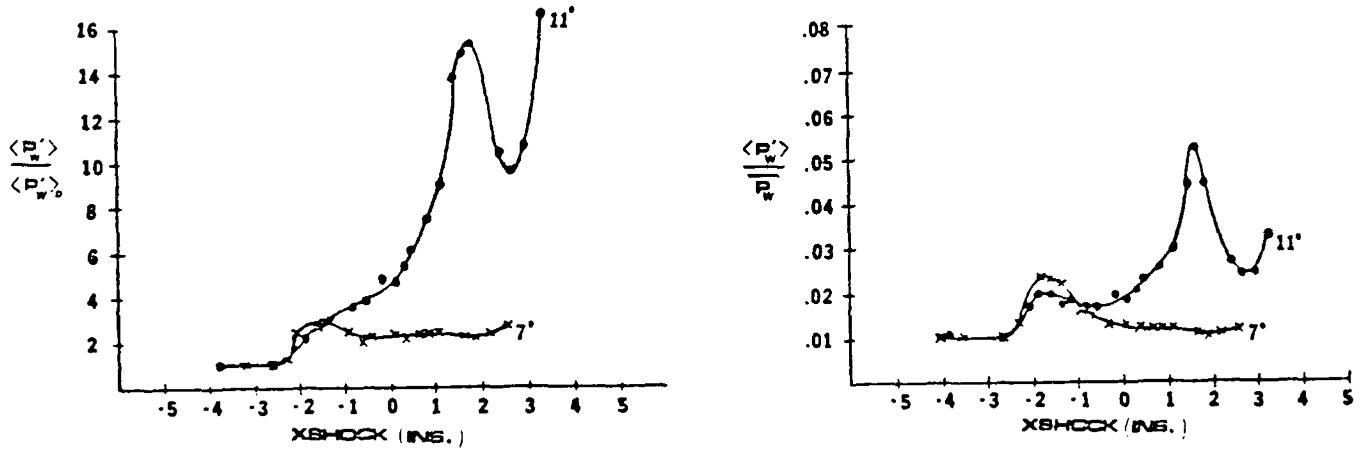


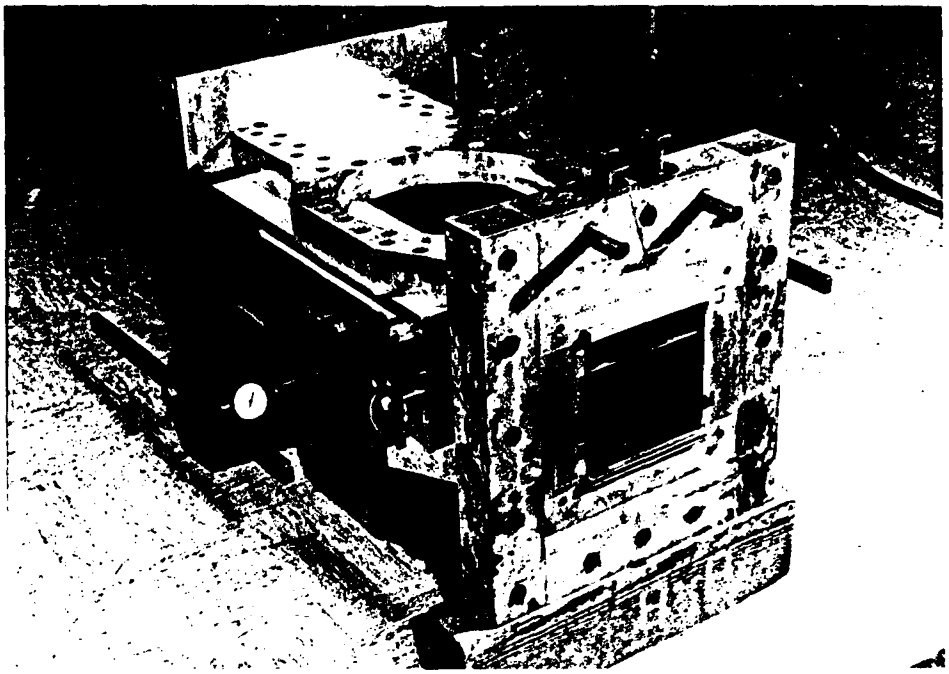
Figure 16. Surface static pressure along the centerline of the symmetric interactions.



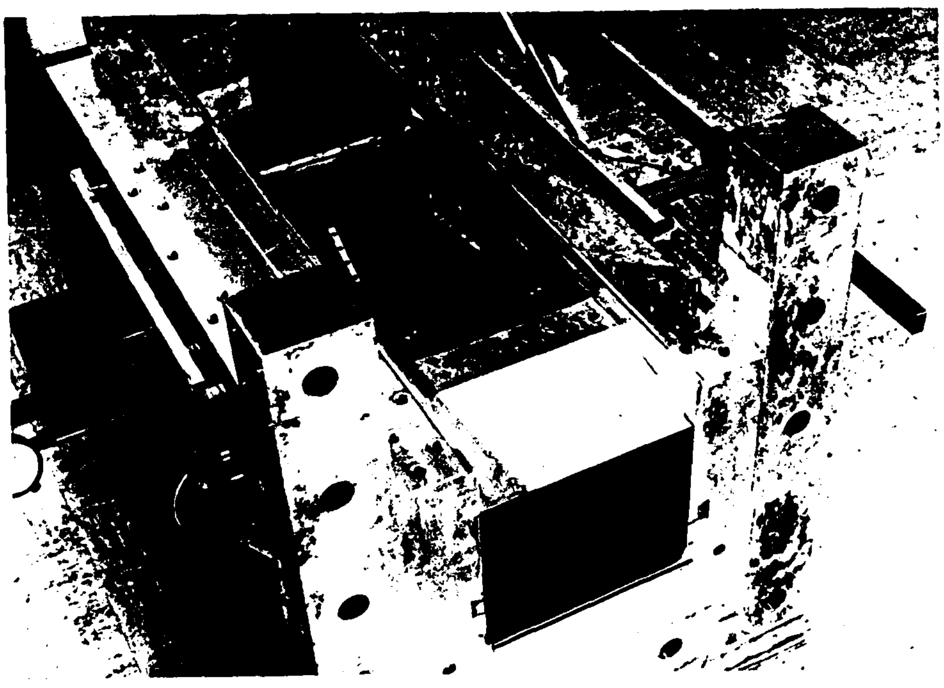
a) Normalized by upstream value

b) Normalized by local mean pressure

Figure 17. Distribution of RMS of wall pressure fluctuation for crossing shock interaction.

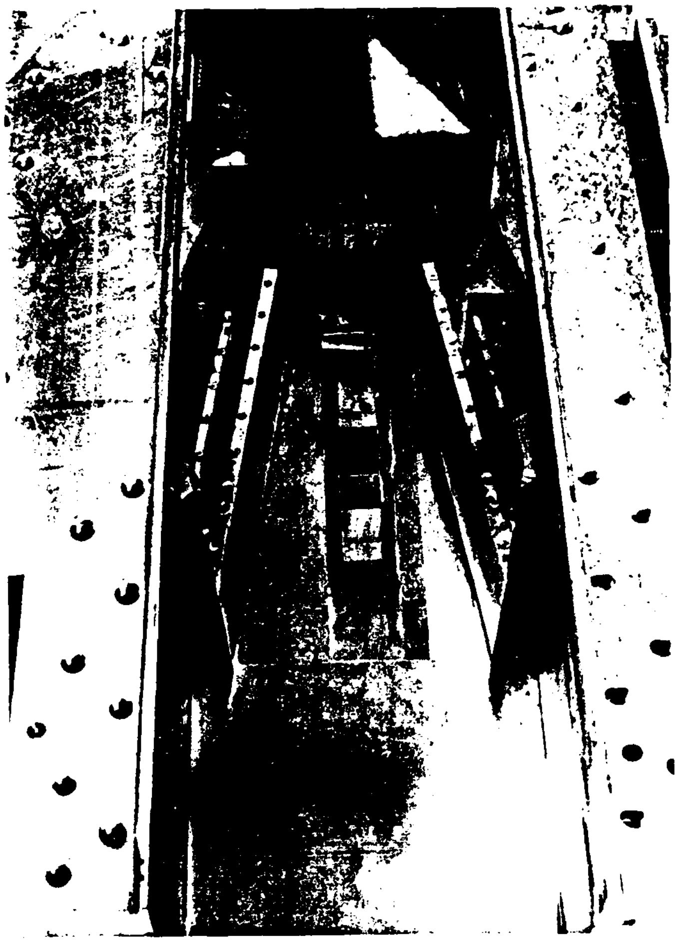


a)



b)

Figure 18. Crossing shock model and test section.



c)

Figure 18. (cont'd)

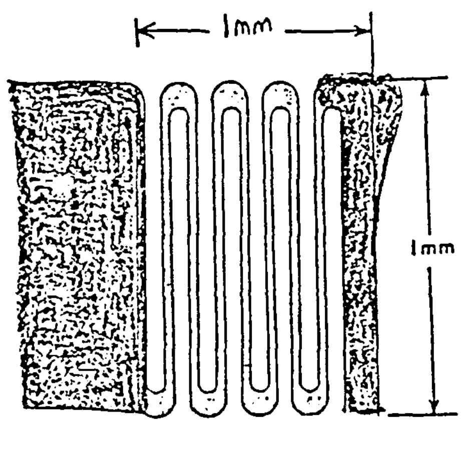


Figure 19. Thins film heat flux gauge design; 1500A^{o} thick, 127 μm wide, Palladium sensor on fused quartz substrate.

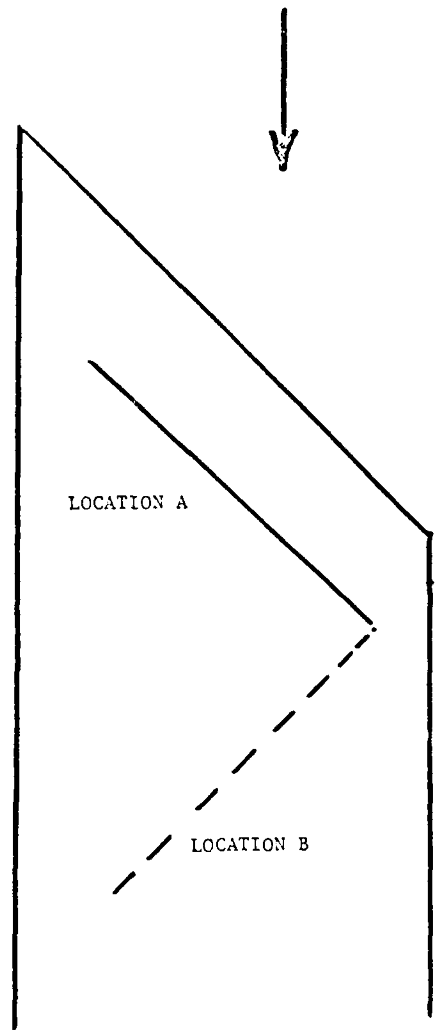


Figure 20. Plate and model geometry for Wang, et al.

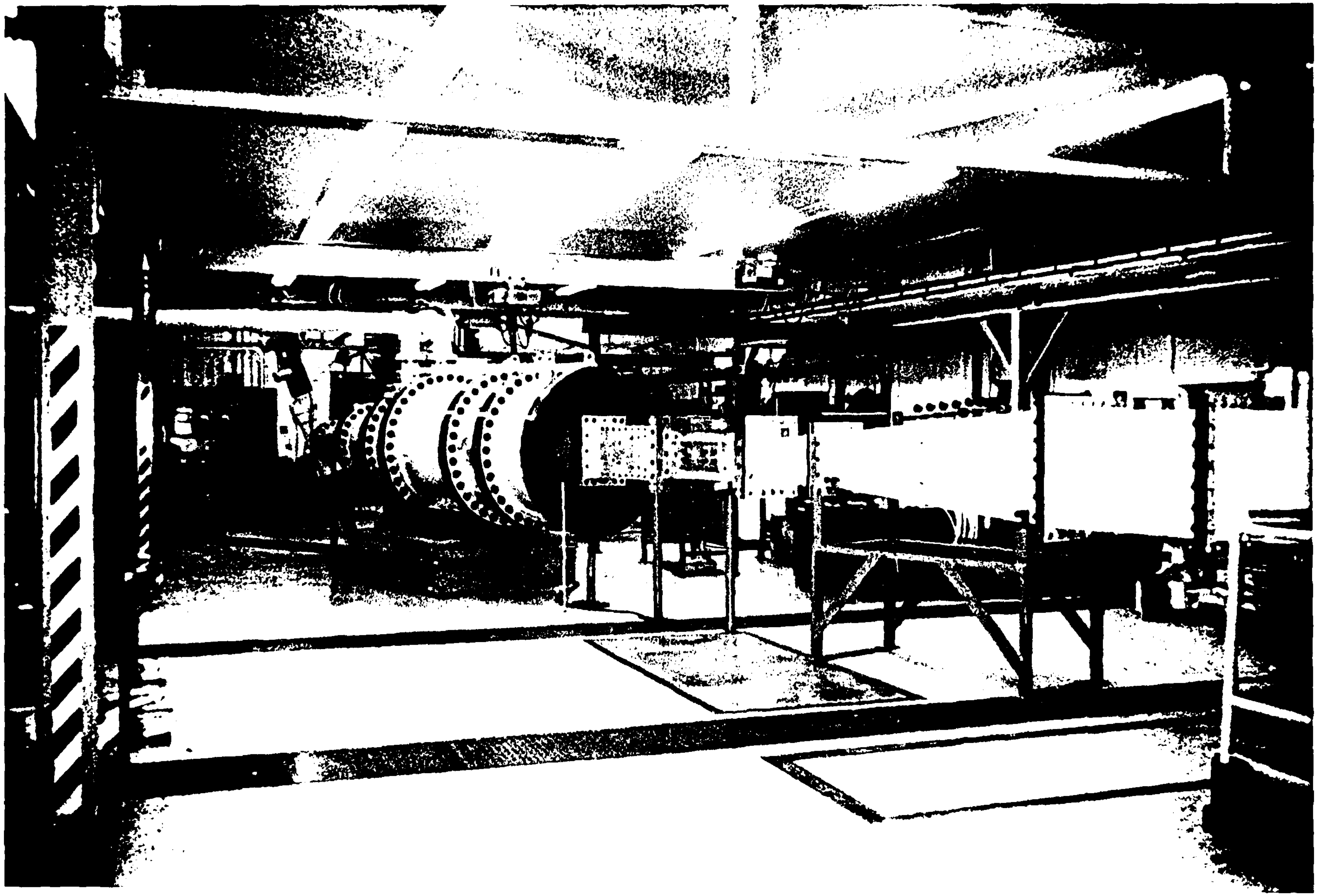


Figure 21. The Low Turbulence Variable Geometry Facility.